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## Fiber-Optic Filter with Tunable Grating

### Field of the Invention

This invention relates to a fiber-optic tunable filter using a fiber Bragg grating (FBG) bonded to an expander having a coefficient of expansion for either temperature or magnetic field.

### Background of the Invention

Fiber optic filters are well known in the art, and may be constructed using a combination of optical fiber and gratings. Using fiber of the previously described type, there are several techniques for creating fiber optic gratings. The earliest type of fiber grating-based filters involved gratings external to the fiber core, which were placed in the vicinity of the cladding as described in the publication "A single mode fiber evanescent grating reflector" by Sorin and Shaw in the Journal of Lightwave Technology LT-3:1041-1045 (1985), and in the U.S. patents by

1 Sorin 4,986,624, Schmadel 4,268,116, and Ishikawa 4,622,663.  
2 All of these disclose periodic gratings which operate in the  
3 evanescent cladding area proximal to the core of the fiber,  
4 yet maintain a separation from the core. A second class of  
5 filters involve internal gratings fabricated within the  
6 optical fiber itself. One technique involves the creation  
7 of an in-fiber grating through the introduction of  
8 modulations of core refractive index, wherein these  
9 modulations are placed along periodic spatial intervals for  
10 the duration of the filter. In-core fiber gratings were  
11 discovered by Hill et al and published as "Photosensitivity  
12 in optical fiber waveguides: Application to reflected filter  
13 fabrication" in Applied Physics Letters 32:647-649 (1978).  
14 These gratings were written internally by interfering two  
15 counter propagating electromagnetic waves within the fiber  
16 core, one of which was produced from reflection of the first  
17 from the fiber endface. However, in-core gratings remained  
18 a curiosity until the work of Meltz et al in the late 1980s,  
19 who showed how to write them externally by the split-  
20 interferometer method involving side-illumination of the  
21 fiber core by two interfering beams produced by a laser as  
22 described in the publication "Formation of Bragg gratings in  
23 optical fibers by a transverse holographic method" in Optics  
24 Letters 14:823-825 (1989). U.S. patents Digiovanm 5,237,576  
25 and Glenn 5,048,913, also disclose Bragg gratings, a class

1 of grating for which the grating structure comprises a  
2 periodic modulation of the index of refraction over the  
3 extent of the grating. Within this class of in-fiber  
4 gratings, most of the art is directed to in-fiber gratings  
5 having the Bragg plane of refractive index modulation  
6 perpendicular to the principal axis of the core of the fiber  
7 optic cable. A new class of grating involves in-fiber  
8 gratings with an angular offset in the plane of refractive  
9 index modulation. This type of angled grating is referred  
10 to as a mode-converting two-mode grating, and, with properly  
11 chosen angle, has the property of converting fundamental-  
12 mode power into second-mode power and visa versa. Whether  
13 internal or external, both types of gratings can be  
14 fabricated as short-period gratings, or long-period  
15 gratings. Short-period gratings reflect the filtered  
16 wavelength into a counter-propagating mode, and, for silica  
17 based optical fibers, have refractive index modulations with  
18 periodicity on the order of a third of the wavelength being  
19 filtered. Long-period gratings have this modulation period  
20 much longer than the filtered wavelength, and convert the  
21 energy of one mode into another mode propagating in the same  
22 direction, i.e., a co-propagating mode, as described in the  
23 publication "Efficient mode conversion in telecommunication  
24 fibre using externally written gratings" by Hill et al in  
25 Electronics Letters 26:1270-1272 (1990). The grating

1 comprises a periodic variation in the index of refraction in  
2 the principal axis of the core of the fiber, such variation  
3 comprising a modulation on the order of 0.1% of the  
4 refractive index of the core, and having a period associated  
5 with either short or long-period gratings, as will be  
6 described later.

7 Tunable fiber-optic filters can be produced in a  
8 variety of ways. Figure 1 shows a fiber optic cable 12  
9 having a core 14 which has a grating 16 written over an  
10 extent  $L_g$  18. The pitch of the grating 16 may be fixed or  
11 variable, and may be incrementally varied by changing the  
12 temperature of the fiber in the region of the grating.  
13 Germanium doped silicon has a coefficient of thermal  
14 expansion of 10ppm/°C. Alternatively, the fiber may be  
15 placed in a variable tension, and this tension causes a  
16 shift in wavelength, as in the case of US Patent No.  
17 6,597,822 by Moslehi et al. In U.S. Pat. No 4,968,623 by  
18 Sorin, the pitch of a grating is varied by applying a  
19 proximal grating mounted on a disk and rotating it to vary  
20 the apparent pitch experienced by the proximal fiber. In  
21 U.S. Pat No 6,011,881 by Moslehi et al, a method for tuning  
22 a fiber optic grating coupled to a variable index material  
23 is disclosed. U.S. Patent 6,411,746 by Chamberlain et al  
24 discloses a method for tuning an optical filter comprising  
25 grating coupled to a heater.

1       It is desired to provide a tunable fiber optic filter  
2 where the strain of a grating is varied through the  
3 expansion of an expander having a large extent which is  
4 coupled to the smaller extent of a Bragg grating. It is  
5 also desired to provide a magnetically tunable fiber-optic  
6 filter where the extent of an expander is the same as, or  
7 greater than, the extent of the fiber Bragg grating.

8       There are many materials known for its magneto-  
9 strictive properties, and among these materials the material  
10 of choice is Terfenol™ (Terfenol is a registered trademark  
11 of Etrema Products [www.etrema.com](http://www.etrema.com), and Terfenol™ information  
12 is available at [www.etrema-usa.com](http://www.etrema-usa.com)). Other magneto-  
13 strictive materials which change length in response to an  
14 externally applied magnetic field are KelvinAll®, Terbi-  
15 um-Dysprosium, and Terbi-um-Dysprosium-Zinc. Figure 13 shows  
16 the magnetostrictive property of  $Tb_{0.3} Dy_{0.7} Fe_{1.9}$  which is  
17 commonly known by the tradename Terfenol-D™. Until  
18 recently, magnetostrictive materials typically produced  
19 lower strains than piezoceramic and electrostrictive  
20 materials. The graph 230 shows the magnetostriction of  
21 Terfenol-D varying from 0 to approximately 1800ppm over the  
22 range 0 to 2000 Oersteds of magnetic field, which is on the  
23 order of 40 times greater magnetostriction than previous  
24 magnetostrictive materials, and a factor of 10 greater than  
25 piezoceramic devices. The graph 230 has a quadratic

1 response for small fields (below 200 Oe), a quasi-linear  
2 response for fields from 200 Oe to 600 Oe, and a saturating  
3 region for fields in excess of 600 Oe. These points are  
4 approximate, and may vary depending on the particular  
5 material used.

#### 6 7 8 Objects of the Invention

9 A first object of the invention is a tunable filter  
10 whose transmission and reflection characteristic can be  
11 modified by the application of thermal energy to an expander  
12 made from a material having a coefficient of expansion which  
13 is greater or lesser than that of the fiber.

14 A second object of the invention is a tunable filter  
15 whose transmission and reflection characteristic may be  
16 modified by the application of magnetic field to an expander  
17 made from a material having a coefficient of expansion to a  
18 magnetic field.

19 A third object of the invention is a tunable filter  
20 where an expander is tightly coupled to a Bragg grating in a  
21 fiber where the grating extent is similar to the extent of  
22 the expander.

23 A fourth object of the invention is a tunable filter  
24 where an expander is coupled at to a fiber at two attachment

1 areas, and the fiber has a Bragg grating positioned between  
2 these two attachment areas.

3 A fifth object of the invention is a tunable filter  
4 where an expander is coupled to an extent reducer at two  
5 attachment areas, and the fiber has a Bragg grating  
6 positioned between the extent of the extent reducer  
7 attachment areas.

8 A sixth object of the invention is a tunable filter  
9 where an expander fabricated from a first material is  
10 coupled to an extent reducer which reduces the extent of the  
11 expander to two attachment areas, and the fiber has a Bragg  
12 grating positioned between the attachment areas of the  
13 extent reducer, and the extent reducer is fabricated from a  
14 second material, where the first and second materials have  
15 substantially different coefficients of thermal expansion.

16 A seventh object of the invention is a tunable filter  
17 where an expander is constructed from several  
18 magnetostrictive rods having a first end and an opposite  
19 end, the rods including a central channel for the  
20 displacement of a fiber with a grating bonded to a first  
21 fiber rod on one side of the grating and a second fiber rod  
22 on the other side of the grating, the first rod extending to  
23 and bonded to the first expander end, and the second fiber  
24 rod extending to and bonded to the opposite expander end.

25

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3 Summary of the Invention

4       A fiber optic cable has a grating written in an area  
5 having an extent  $L_g$ , and this grating is mechanically  
6 coupled over the extent  $L_g$  in tension to a structure known  
7 as an expander, which performs the function of modifying the  
8 tension in the fiber grating through the application of an  
9 external control parameter such as temperature or magnetic  
10 field which varies the length of the expander. The expander  
11 changes dimension in accordance with the coefficient of  
12 expansion of the expander. For the case of tuning the Bragg  
13 grating using temperature control, the expander is made from  
14 a material having a coefficient of thermal expansion greater  
15 than or opposite to the coefficient of thermal expansion of  
16 the fiber and a heat source is coupled to the expander,  
17 causing the grating period to change. For a tunable Bragg  
18 grating with magnetic control, the expander is made from a  
19 material having a coefficient of magnetic field expansion  
20 and a magnetic field is applied. For the temperature  
21 controlled tunable filter, a suitable material for the  
22 expander may comprise a material with a coefficient of  
23 thermal expansion which is substantially greater or lesser  
24 than the coefficient of thermal expansion of the fiber,  
25 where the expander is coupled to a thermal heater.



1 Alternatively, for a magnetically tunable optical filter,  
2 the expander may be fabricated from a magnetostrictive  
3 material such as Terfenol-D™.

4 In another embodiment, a magnification of tuning range  
5 is accomplished by making the expander extent large compared  
6 to the grating extent, where the expander is coupled to an  
7 extent reducer, which reduces the extent of the expander to  
8 the extent of the grating. The expander is made from a  
9 first material having a coefficient of expansion for the  
10 applied control of temperature or magnetic field, and the  
11 expansion reducer is made from a second material for which  
12 its extent is substantially unchanged by the applied  
13 control. In this manner, the tuning range of the fiber  
14 grating is increased by the ratio of the extent of the  
15 expander to the extent of the grating.

#### 20 Brief Description of the Drawings

21 Figure 1 shows a prior art optical fiber with a fiber  
22 Bragg grating.

23 Figure 2 shows a side view of an embodiment of the  
24 present invention.

1        Figure 3 shows a section view of an embodiment of a  
2 tunable filter based on figure 2.

3        Figure 4 shows the section view of another embodiment  
4 of the tunable filter of figure 2.

5        Figure 5 shows the section view of another embodiment  
6 of the tunable filter of figure 2.

7        Figure 6 shows the tunable filter where the tuning  
8 medium is a magnetically sensitive material in combination  
9 with a source of magnetic field.

10       Figure 7 shows the tunable filter where the tuning  
11 medium is a thermally sensitive material in combination with  
12 a thermal heater.

13       Figure 8a shows the transmission and reflection  
14 response of a short period fiber Bragg grating.

15       Figure 8b shows the tuning characteristics for an  
16 expander having a positive expansion coefficient.

17       Figure 8c shows the tuning characteristics for an  
18 expander having a negative expansion coefficient.

19       Figure 9 shows a view of a tunable filter using three  
20 magnetostrictive rods.

21       Figure 10 shows a detail of the extent reducers of  
22 figure 9.

23       Figure 11 is a cross section detail of figure 9.

24       Figure 12 is a cross section detail of figure 9.

1        Figure 13 is a graph of the magnetostrictive properties  
2 of Terfenol-D™.

3  
4  
5    Detailed Description of the Invention

6        Figure 2 shows a fiber 22 having a core 24, and a  
7 grating 28 applied to the core. An expansion device 26 is  
8 mechanically coupled to the fiber 22 over the extent of the  
9 grating 28.

10       Figure 3 shows one embodiment 30 of the expansion  
11 device 26 of figure 2, where the grating 43 has an extent  
12 42, and the expansion device comprises an expander 36 having  
13 a first attachment point 38 and a second attachment point  
14 40, and the attachment points are separated by a variable  
15 extent 44. The fiber 32 is placed in tension prior to the  
16 application of an adhesive such as epoxy to secure the fiber  
17 32 to the first and second attachment points 38 and 40,  
18 respectively. The expander 36 may be fabricated from a  
19 material with a high coefficient of thermal expansion such  
20 as aluminum with 22 ppm/°C or zinc, with a coefficient of  
21 thermal expansion of 30 ppm/°C. Since the fiber has an  
22 intrinsic coefficient of thermal expansion of 10 ppm per °C,  
23 it can be seen that the grating will be tunable to the  
24 extent of the difference between these two coefficients of  
25 thermal expansion, or 20 ppm per °C for the case of zinc.

1        Figure 4 shows another embodiment 50 where the fiber 52  
2        has a core 54 and a grating 61 is written over an extent  $L_g$   
3        60. The expander 56 is coupled to the fiber 52 over the  
4        entire extent 60 of the grating 61 using an adhesive such as  
5        epoxy 58, or any other material which is suitable for  
6        bonding the expander 56 to the fiber 52. As before, the  
7        fiber 52 may be placed in tension prior to applying a  
8        bonding agent 58 between the fiber 52 and expander 56. The  
9        tension applied to the fiber 52 prior to bonding to the  
10       expander 56 should be sufficient to keep the fiber 52 in  
11       tension over the entire temperature operating range of the  
12       tunable fiber device, since the wavelength tuning control  
13       relies on the presence of tension in the fiber.

14       Figure 5 shows another embodiment 70 for a tunable  
15       filter for a fiber 72 having a core 74 with a grating 83  
16       where the expander 78 has an extent 84. In practice, the  
17       application of a temperature or magnetic field will cause  
18       the extent 84 to vary, as was described earlier. A first  
19       extent reducer 76 and second extent reducer 80 reduce the  
20       extent 84 of the expander 78 to a first attachment point 86  
21       and a second attachment point 88, which are approximately  
22       the same separation as the extent 82 of the grating 83. The  
23       expander 78 is fabricated from a material which is highly  
24       sensitive to the control parameter of temperature or  
25       magnetic field, and the extent reducers 76 and 80 are

1 fabricated from materials which are unchanged by the control  
2 parameters, or may even have an unequal and opposite value  
3 of expansion. In this manner, the change in extent of the  
4 expander 78 is applied only to the grating, and this  
5 magnifies the effect of this expansion by the ratio of the  
6 extent of the expander to the extent of the grating. For  
7 example, if the grating extent were  $L_g$  with a coefficient of  
8 expansion  $\alpha_g$ , while the expander had an extent  $L_{exp}$  with a  
9 coefficient of expansion  $\alpha_{exp}$ , the change in fiber pitch  
10 from a change in temperature or magnetic field influence  
11 would be:

$$12 \quad \Delta g = L_{exp} (T1-T2)\alpha_{exp} - L_g (T1-T2)\alpha_g$$

13

14 where:

15  $\Delta g$  is the change in grating length;

16  $L_{exp}$  is the length or extent of the expander;

17  $L_g$  is the length or extent of the grating;

18  $(T1-T2)$  is the temperature (or magnetic field)  
19 difference;

20  $\alpha_{exp}$  is the coefficient of expansion for the expander;

21  $\alpha_g$  is the coefficient of expansion for the grating.

22 Then, the change in grating period would be:

1            $\Delta\lambda/\lambda = \Delta g/L_g$

2           such that if  $K = (L_{\text{exp}}\alpha_{\text{exp}}/L_g\alpha_g)$

3            $\Delta\lambda/\lambda = (K-1)\alpha_g (T_1-T_2)$

4           It can be seen that K represents the multiplicative  
5 effect of the ratios of coefficients of expansion and ratio  
6 of extents of the expander compared to the extent of the  
7 grating. In this manner, a grating length can be chosen  
8 based on desired filter characteristic, and an extender  
9 length can be chosen based on a desired tuning range.

10          For the expansion devices shown in figures 3, 4, and 5,  
11 it is clear to one skilled in the art of optical devices  
12 that the coefficients of expansion  $\alpha_{\text{exp}}$  and  $\alpha_g$  are taken to  
13 be with regard to a general environmental parameter, which  
14 may be temperature or magnetic field, and for optimal tuning  
15 range, a material having a suitable coefficient of expansion  
16 should be optimized to the control method. Tuning devices  
17 relying on thermal coefficients of expansion tend to be slow  
18 because of the latent heat of the materials used in the  
19 expander, while tuning devices which rely on magnetic field  
20 changes may have faster response times. While the  
21 descriptions of coefficient of expansion have been general,  
22 it is understood that the coefficient of expansion is  
23 related to the method of control. A material such as zinc  
24 has a coefficient of thermal expansion of 20 ppm/°C, making

1 it suitable for thermal control, while a material such as  
2 Terfenol-D™ has a coefficient of magnetic field expansion of  
3 1 ppm per Oersted of applied magnetic field. The details of  
4 each type of control are discussed in figures 6 and 7.

5 Figure 6 shows the tunable filter where the applied  
6 control is magnetic field 106. A power source 96 is coupled  
7 to a winding 114 via leads 98 and 100. The winding 114  
8 produces a magnetic field 106, which couples to the  
9 expansion device 104, which may be any of the structures  
10 described in figures 3, 4, or 5, and causes a change in the  
11 extent of the expanders 36, 56, and 78, respectively. This  
12 change in extent causes the optical fiber 32 of figure 3, 52  
13 of figure 4, and 72 of figure 5 to experience a change in  
14 tension, thereby changing the pitch of the gratings 43 of  
15 figure 3, 61 of figure 4, and 83 of figure 5. The  
16 mathematics of this change were described in detail for the  
17 case of figure 5, and figures 4 and 3 are simple reductions  
18 of the case of figure 5 where

19  $(L_{\text{exp}}/L_g) \approx 1$ , and hence

20  $K = (\alpha_{\text{exp}}/\alpha_g)$ .

21 Also shown in figure 6 is an input excitation 108, a  
22 reflected wavelength 110, and a transmitted wavelength 112.  
23 As the grating pitch is varied according to the change in

1 expander length, the reflected wavelength 110 and  
2 transmitted wavelength 112 center wavelengths are modified.

3       Figure 7 shows a thermally controlled expansion device  
4 126, where a power source 128 is coupled to a heater 134 via  
5 leads 130 and 132. The thermal energy is coupled into the  
6 expansion device 126, resulting in a change in the dimension  
7 of the expander of the expansion device, as was described in  
8 figures 3,4, and 5. An input excitation 136 results in a  
9 reflected wavelength 138, and a transmitted wavelength 140.  
10 As the grating pitch is varied according to the change in  
11 expander length, the reflected wavelength 138 and  
12 transmitted wavelength 140 center wavelengths are modified.

13       Figure 8a shows the tuning effect of applying the  
14 control of magnetic field in figure 6 or temperature in  
15 figure 7. At a given operating point with a fixed control,  
16 a wideband source 150 is applied as either 108 of figure 6  
17 or 136 of figure 7. The interaction of the optical energy  
18 with the grating produces a reflected spectrum 154,  
19 corresponding to the reflected energy found at 110 of figure  
20 6, or reflected energy found at 138 of figure 7. The  
21 spectral response of the filter is centered about a center  
22 wavelength  $\lambda_c$  151. The remaining transmitted energy 152 of  
23 figure 8a corresponds to the output wave energy 112 of  
24 figure 6 or 140 of figure 7. These figures reflect the  
25 characteristics of short-period gratings, for which the



1 behavior is reflection of optical energy at a wavelength  
2 associated with the grating, as is known to one skilled in  
3 the art. For long period gratings, the behavior is the  
4 opposite - most of the energy is reflected, and a narrow  
5 band of energy is transmitted through the gratings. Either  
6 type of grating is suitable for the embodiments of figures  
7 3, 4, and 5, and it is clear to one skilled in the art that  
8 the tuning mechanism is identical, however the  
9 characteristics of these two types of filters is different.

10 Figure 8b shows the center wavelength tunability with  
11 an external control, where the coefficients of expansion  
12 have positive characteristics, such as zinc for thermal  
13 control, or Terfenol™ for magnetic control using a  
14 magnetostrictive material. In this example, the application  
15 of an increasing control 162 produces a longer grating,  
16 resulting in a longer center wavelength 160, as shown by the  
17 curve 164.

18 Figure 8c shows the center wavelength tunability with  
19 an external control, where the coefficients of expansion  
20 have negative characteristics, such as zinc for thermal  
21 control, or Terfenol™ for magnetic control. In this  
22 example, the application of an increasing control 172  
23 produces a shorter grating, resulting in a shorter center  
24 wavelength 170, as shown by the curve 174.

1       The figures and descriptions are shown for illustration  
2 only, to enable the reader to understand the invention in a  
3 particular form, for the purposes of describing a specific  
4 implementation, and are not intended to restrict the  
5 invention to only those implementations described in the  
6 figures. For example, the structures of figures 3, 4, and 5  
7 are shown as a cross section view of circularly symmetric  
8 cylinder of figure 2, however it is clear that it is  
9 possible to construct the structures of figures 3, 4, and 5  
10 as half-cylinders, or as rectangular solids, or any shape  
11 which couples a large change of extent over a short change  
12 of extent. The Bragg gratings may be short period or long  
13 period as known in the prior art, and may be written on the  
14 fiber core or fiber cladding, in accordance with the prior  
15 art of fiber Bragg gratings. While the examples shown are  
16 for controlling the tuning of the grating using an  
17 externally applied magnetic field or thermal source, the  
18 implementations may also be used to form a sensor, where the  
19 ambient environment contains a temperature or magnetic field  
20 which is measured by the device shown. For use as a  
21 magnetic field sensor, the implementations of figures 3, 4,  
22 and 5 would be used, without the external magnetic field  
23 generator 114, or power source 96 shown in figure 6. For  
24 use as a temperature sensor, the implementations of figures  
25 3, 4, and 5 would be used, without the power source 128 and

1 heater 134 shown in figure 7. In this manner, a sensor for  
2 magnetic or temperature could be realized.

3 Figure 9 shows an additional embodiment of the geometry  
4 described in figure 5. Tunable filter 200 comprises three  
5 equal length expander rods 214, 216, and 218, each rod  
6 having a first end and a second end opposed to the first  
7 end. The expander rods may be made from a magnetostrictive  
8 material such as Terfenol™, as described earlier. A fiber  
9 202 having a grating 204 is threaded through a first tube  
10 206 and a second tube 208, and the fiber is bonded to the  
11 tube at the tube/fiber interface 224 and 226. The tube and  
12 fiber assembly include end stops 210 and 212 which are  
13 bonded to the tubes 206 and 208, respectively. The end  
14 stops 210 and 212 are in contact with first and second ends  
15 of the three magnetostrictive rods 214, 216, and 218.

16 Figure 10 shows the detail of the fiber 202, grating  
17 204, first bonding 224 to first tube 206, first end stop  
18 210, second bonding 226 to second tube 208, and second end  
19 stop 212. The tubes 206 and 208 may continue beyond the end  
20 stops 210 and 212, respectively. Grating extent 220 and  
21 expander extent 222 operate as was described in the earlier  
22 figure 5. When a control field or temperature is applied to  
23 the expanders 214, 216, 218, they uniformly expand in length  
24 222, since the expanders 214, 216, and 218 are bonded to the  
25 end stops 210 and 212. The rods 206 and 208 are not

1 connected to the expander at any points other than the end  
2 stops 210 and 212, and the rods are fabricated from a  
3 material which is not influenced by the control applied to  
4 the expander rods 214, 216, 218. In this manner, the  
5 expanders 214, 216, 218 change length 222, which is  
6 translated to the grating extent 220, thereby causing a  
7 large change in expander length to be entirely applied to  
8 the grating 204.

9 Figure 11 shows the section a-a and d-d through the end  
10 stops shown on figure 9. Expanders 214, 216, and 218 are in  
11 contact with first stop 210 and first rod 206 in section a-  
12 a, and with second stop 212 and second rod 208 in section d-  
13 d of figure 9.

14 Figure 12 shows the sections b-b and c-c through the  
15 expanders 214, 216, 218 and the first rod 206 which is  
16 bonded to fiber 202 on one end of the grating 204 for  
17 section b-b, and the second rod 208 which is bonded to fiber  
18 202 on the other end of the grating 204 for section c-c of  
19 figure 9. From the principles of the invention, there is no  
20 bonding contact between the fiber tube 208 and expander rods  
21 214, 216, 218 at any points other than the ends of the  
22 expander rods where they are affixed with end stops 210 and  
23 212.

24 It is clear to one skilled in the art of tunable  
25 filters that it is possible to use many different shapes and

1 numbers of expanders 214, 216, 218 beyond the use of 3 rods  
2 as shown, and figures 9 through 12 show just one alternate  
3 method of realizing the expander shown in figure 5, which  
4 similarly comprises an expander and a translator coupled to  
5 a grating.

6 In figure 9, it is also possible to bond the ends of  
7 the expanders to the fiber tubes 206 and 208 at the end  
8 stops 210 and 212 in may different ways than shown.  
9 Directly bonding the fiber tubes 206 and 208 to the expander  
10 first end and expander second end is also possible, and this  
11 bonding may be done with epoxy, a mechanical bond, or any  
12 other means of bonding the fiber tube to the expander end.

13 It is believed that the best mode of figure 9 includes  
14 bonding the fiber 202 exclusively at the fiber rods 206, 208  
15 adjacent to the grating 204, rather than filling the fiber  
16 rods 206 and 208 with epoxy beyond the bonding points 224  
17 and 226.

18 For each of the attachments of expanders to expansion  
19 reducers 76 and 80, as in figure 5, or rods 206 and 208,  
20 there are many forms of bonding known in the art for making  
21 these attachments. Available bonding methods include the  
22 use of epoxies and welding agents, as well as any other  
23 bonding method known. Another bonding type is mechanical  
24 bonding, as where the fiber 202 of figure 9 is in tension,  
25 and the end stops 212 and 210 have extents which are within

1 the extent of the ends of the expander rods 214, 216, 218,  
2 thereby securing the end stops 212 and 210 to the expanders  
3 214, 216, 218 through the use of the holding tension of the  
4 fiber 202.

5 The use of materials for the expanders (56 of figure 4,  
6 78 of figure 5, 214, 216, 218 of figure 9) and expansion  
7 reducers (76 and 80 of figure 5, 206 and 208 of figure 9)  
8 requires that the effect of the expanders not be reduced by  
9 the extent of the expansion reducers. For example, if the  
10 expanders and expansion reducers were made from materials  
11 having similar coefficients of expansion, the expander and  
12 expansion reducers would largely cancel each other out. It  
13 is preferred to use an expander and expansion reducer where  
14 the ratio of coefficients of expansion for the expander to  
15 the expansion reducer is greater than 2.